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Deep Convection in the Ocean

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LONG-TERM GOALS

Our long-term objective is to understand how deep convection, induced by strong buoyancy forcing at the ocean surface, influences the ocean circulation through convective plumes and geostrophic eddies.

OBJECTIVES

Issues specific to oceanic deep convection are the relatively strong role of rotation, where convective Rossby numbers appropriate to the vertical motions may fall below unity; the highly intermittent nature of the forcing with strong impulses coming during the passage of atmospheric weather systems; the possible highly localized occurrence of deep convection; and the subsequent spatial redistribution and mixing of convected water by geostrophic mesoscale dynamics, which arise in part from instability of the localized convection regions. Our particular research projects are computational investigations intended to (1) quantify the extent to which penetrative mixing occurs at the base of a rotating convective layer, sharpening the pycnocline and entraining denser fluid from below (2) determine how space/time intermittency in either the surface buoyancy flux or the preexisting ocean stratification and circulation relate to the degree of localization of deep convection, and (3) explore the circumstances under which localized convected regions are persistent after the buoyancy forcing abates or undergo erosion through subsequent horizontal mixing and restratification of the gyre interior.

APPROACH

High-resolution numerical simulations using the Boussinesq model developed in cooperation with our colleagues, Keith Julien and Joseph Werne of NCAR, are carried out on grids of 256 x 256 x 129 over domains of 2km x 2km x 1km to investigate plume-scale dynamics. Conditionally sampled composite techniques are used to isolate the plume structures. The Boussinesq model is also used at coarser resolution over domains of 50km x 50km x 2km to examine interactions between convection and simple examples of geostrophic circulation.

For more complex inhomogeneities in the initial conditions, larger horizontal domains and longer evolution times are required. Limited computational resolution then prevents resolution down to the plume scale, and a parameterization of the convective mixing is applied in these large domains (up to 200km x 200km x 4km). The use of an implicit gravity-wave Boussinesq model developed by Alistair Adcroft at MIT enables the use of longer timesteps, while representing the geostrophic adjustment process. We are studying the interaction between the vertical homogenization forced by the surface buoyancy loss and the pre-existing eddy field, including the development of baroclinic instability, the horizontal homogenization of the mixed fluid by the eddy dynamics, and the possibility of persistence of isolated cores of mixed fluid. We then compare model solutions for these phenomena with observations from the Labrador Sea ARI field program.

WORK COMPLETED

(1) We completed a series of numerical simulations of convection forced by homogeneous cooling into a volume of fluid containing a single geostrophic, cold-core eddy. This provides extensive evidence of localization of convection by anomalies in the preexisting ocean stratification. These results are described in the article "Localization of deep convection by a mesoscale eddy" (Legg, McWilliams, and Gao, 1998).

(2) We completed an analysis of the plume structures of turbulent convection. Plume structures are educed from the turbulent fields associated with convection by conditionally sampling for maxima in the downward vertical velocity and calculating a composite plume. Using the composite to identify typical plumes, we have obtained a census of the plume population and examined statistics including the amplitude, vertical tilt, horizontal radius, axisymmetry, and vertical length. The results of this plume analysis are described in an article "Plumes in rotating convection: Part I Ensemble statistics and balances"(Julien, Legg, McWilliams, and Werne, 1999).

(3) We collaborated with Ken Fischer and colleagues at the Environmental Research Institute of Michigan by sharing surface fields from our localized convection simulations, which they have used to simulate Synthetic Aperture Radar (SAR) images of the convecting fields. These simulations investigate the feasibility of using SAR to observe the structures of open-ocean deep convection. These results are described in the article "Modeled radar surface signature of deep ocean convection", (Fischer, Legg, Munk, Shuchman, Garwood, and Palshook 1999).

(4) We completed a series of calculations of convection in the presence of a single mesoscale eddy where the eddies are associated with compensating anomalies in temperature and salinity, in addition to the density anomaly as studied in our previous work (Legg, McWilliams and Gao, 1998). We examined the subsequent density-compensated variability. These results are described in an article "Temperature and salinity variability in heterogeneous convection", (Legg and McWilliams, 1999a).

(5) We completed a series of calculations over larger area domains (100km x 100km) containing ensembles of several dense and light core eddies and comparison calculations without any eddies. In some calculations, convective buoyancy loss is applied to the upper surface; in others no forcing is applied and, in some, buoyancy loss is of only limited duration. These calculations have revealed a rich interaction between the convection and geostrophic eddy dynamics. The results of this study are described in an article "Convective modifications of a geostrophic eddy field", (Legg and McWilliams, 1999b.)

(6) Using solutions generated in the study of the interaction between convection and many geostrophic eddies, we examined the response of isobaric drifters to the plume and eddy scale motion, both at the surface and at depths of 1000m, using a Lagrangian particle code with particles constrained to a particular vertical level. We are comparing these drifter statistics with those obtained by Breck Owens, Russ Davis, and Kara Lavender using PALACE floats in the Labrador Sea. An article describing the eddy signatures of isobaric floats is currently in progress.

RESULTS

(1) Localization of Convection

Our simulations of convection in the presence of geostrophic eddies indicate that such stratification anomalies may provide a mechanism for the long hypothesised preconditioning of the ocean for locally deeper convection. Such anomalies also provide a mechanism for restratification of the convectively mixed region, as vertical convection is replaced first by slant-wise convection and then by baroclinic instability with an associated secondary circulation. Instability eddies carry the dense fluid outwards causing the region of deepest vertical buoyancy flux to migrate outwards. The horizontally averaged density field which results has lighter surface layers, and denser deeper layers than in those generated by horizontally homogeneous convection.

(2) Plume Structures at Low Rossby Number

The plume structure identification algorithm allows us to examine the life cycle of a plume, from emergence from the boundary layer, through its migration across the convective layer. We compared the properties of the evolution of the typical plume vertical momentum, volume, and heat content with an idealized entraining plume model such as those summarized in Turner, 1986. Results indicate that, initially, entrainment leads to expansion of the plume, but for strongly rotating plumes this entrainment quickly ceases, and is replaced by strong mixing between the plume and environment which modifies plume properties with no change in volume. Examination of individual plume lifecycles and the fate of particles contained within such plumes indicates that mixing events are associated with plume-plume interactions, such as mergers, filamentation and shearing, caused by the cyclonic vortices associated with the plumes.

Comparison of terms in the vertical momentum equation indicate the buoyancy force acting on the plume is largely balanced by a combination of pressure drag and momentum exchange with the environment. The resultant acceleration is, therefore, significantly reduced. Our solutions of strongly rotating penetrative convection (Julien et al., 1996) have previously indicated significantly less penetrative convection as the Rossby number is decreased: both increased detrainment of plume fluid and suppressed plume acceleration are possible candidates for this decreased penetration.

(3) Simulated Synthetic Aperture Radar (SAR) Fields

The simulated SAR images reveal clearly the strong shear and strain in the surface velocity fields of localized convection associated with the generation of cyclonic vorticity in the regions converging into plume and baroclinic eddy downwelling regions. Eddies, fronts and plumes can all be identified and differentiated in these images.

(4) Temperature and Salinity Fine-Structure

When both ambient stratification and a dense core eddy are associated with both salinity and temperature stratification, significant variability can be generated in the temperature and salinity fields without any corresponding density variability. This density-compensated variability can be generated through either vertical mixing or baroclinic eddy processes. We developed a simple parcel exchange theory to predict the magnitude of density-compensated variability. The mechanisms by which variability is created in vertical mixing regions and baroclinic eddy dominated regions differs. In vertical mixing regions parcels of water from the surface are exchanged, via convection plumes, with parcels of the same density from the stable stratification at the base of the convective layer base. In the baroclinic eddy region the parcels are exchanged along isopycnals between the center of the eddy near the surface and outside the eddy below the surface, creating interleaving of inner and outer material. Comparison between the parcel exchange model predictions and simulated variability shows that the vertical mixing region is more efficient at dissipating this variability.

(5) Convective Modifications of a Geostrophic Eddy Field

For a single isolated dense core eddy, the application of surface buoyancy forcing can destabilize a baroclinic eddy through erosion of the surface stratification and cause it to break up via baroclinic instability. When cooling ceases the remaining eddy fragments rapidly coalesce so that a few isolated eddy cores can persist. The fluid around the eddy cores is, however, much more efficiently mixed (horizontally as well as vertically) than in the absence of convective forcing. This efficient mixing is a result of a very energetic barotropic horizontal velocity field which develops when convective forcing is applied. We show that without any eddies in the initial conditions, no barotropic velocity field is generated. Convective mixing causes a direct input of kinetic energy on the relatively small scales of convective plumes. Yet at these scales, where flow is strongly 3-dimensional, the kinetic energy is rapidly dissipated. When eddies are present, convective forcing acts as a catalyst for the release of available potential energy from the eddies, via baroclinic instability. This kinetic energy input is at the larger scales dominated by geostrophic dynamics, and hence it persists or cascades to even larger scales instead of being dissipated.

(6) Behavior of Floats in Convecting Flows

Our investigations of isobaric floats in the presence of convection localized by mesoscale eddies reveal a tendency for floats to congregate in the convergent regions associated with downwelling fronts. These fronts are associated with cooler than average fluid; hence, the ensemble mean temperature measured by the floats diverges from the Eulerian mean–an important consideration when interpreting observations made by such isobaric floats. As a result the net heat flux deduced from the floats is about half that found from the Eulerian measurements. In flows with considerable eddy structure, the dispersion of floats can also reveal the process of lateral exchange and restratification.

IMPACTS

Our research on convective dynamics should improve understanding of both the observed features of convection and the net effects of these small-scale features on water mass transformation. This understanding provides a firmer basis for predictions of sub-polar circulations and tracer distributions and the global thermohaline circulation.

TRANSITIONS

These results are being shared with members of the ONR Labrador Deep Convection ARI. Our results are included in the article documenting the Labrador Sea convection experiment (Labsea Group, 1998). Our recent results are being used to interpret the results of mooring measurements (Lilly et al., 1998), especially the appearance of strong barotropic eddy velocities during convection periods, and CTD measurements (Pickart et al., 1998), in particular, the structure in temperature and salinity fields. Float studies are being compared with the PALACE floats of Davis, Lavender and Owens, funded by ONR.

RELATED PROJECTS

This work was carried out in collaboration with the "Mesoscale variability in the Labrador Sea" project, Legg PI, WHOI.

ONR Deep Convection ARI

Our simulations of convection localized by one or more mesoscale eddies provide scenarios for comparison with observations, both of the small scale velocity and temperature fields, and remote sensing signatures of the chimney scale circulation and baroclinic instability eddies. These simulations encourage the evaluation of the pre-convection eddy field for comparison with the later localized convection regions. Our plume structure analysis provides detailed statistics on plume property distributions for comparison with data from observations.

ONR Marine Boundary Layer ARI

Our studies of deep convection driven by surface cooling overlap with studies of the oceanic and atmospheric planetary boundary layers. We are engaged in a long-standing partnership with Chin-Hoh Moeng and Peter Sullivan of NCAR, making Large Eddy Simulations of boundary-layer turbulence and comparisons with the field observations made in this ONR program.

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14. ABSTRACT Deep-open ocean convection, the process by which vigorous vertical mixing occurs down to great depths in response to wintertime surface buoyancy losses in the sub-polar seas, is a significant mechanism of water mass transformation. The resultant newly mixed deep water masses form a component of the thermohaline circulation, and hence it is essential to understand the deep convection process if the variability of the meridional circulation, and associated climate fluctuations are to be understood. The rates at which the deep water masses are renewed depend on a complex interaction between processes of different spatial and temporal scales, including thermal plumes associated with vertical convection, baroclinic eddies, and larger scale gyre circulations. The mechanism by which these scales of motion interact and lead to mixing in both vertical and horizontal, as well as the rate at which newly mixed water leaves the formation site, are present subjects of considerable uncertainty. Our accomplishments in studying deep convection include: localization of convection by mesoscale preconditioning; demonstration of the energization of barotropic velocity field by convective interaction with pre-existing eddy field; and identification of the role of both eddies and plumes in generating density-compensated tracer variability.

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